PPSP-MP-16

EVALUATION OF THE GAUSSIAN PLUME MODEL AT MARYLAND POWER PLANTS

Prepared By

Martin Marietta Corporation
Environmental Technology Center
1450 South Rolling Road
Baltimore, Maryland 21227

Based on Measurements by

Environmental Measurements, Inc.
Annapolis, Maryland 21401

March 1977

MARYLAND POWER PLANT SITING PROGRAM

DEPARTMENT OF NATURAL RESOURCES ■ DEPARTMENT OF HEALTH AND MENTAL HYGIENE ■ DEPARTMENT OF ECONOMIC AND COMMUNITY DEVELOPMENT ■ DEPARTMENT OF STATE PLANNING ■ COMPTROLLER OF THE TREASURY ■ PUBLIC SERVICE COMMISSION ■ DEPARTMENT OF TRANSPORTATION

PPSP-MP-16

EVALUATION OF THE GAUSSIAN PLUME MODEL AT MARYLAND POWER PLANTS

By

Jeffrey C. Weil
Martin Marietta Corporation
Environmental Technology Center
1450 South Rolling Road
Baltimore, Maryland 21227

Based on Measurements by

Environmental Measurements, Inc.
2 Lincoln Court
Annapolis, Maryland 21401

March 1977

FOREWORD

This report, comparing mathematical dispersion model calculations to field measurements of ground-level SO_2 concentrations downwind of three Maryland power plants, was prepared for the Maryland Power Plant Siting Program, Department of Natural Resources, by the Environmental Technology Center, Martin Marietta Corporation, under Contract Number 1-72-02(77).

ACKNOWLEDGEMENTS

The author wishes to acknowledge the support and cooperation of Environmental Measurements, Incorporated, who provided the field measurements used in this report. Sincere thanks are extended to T. J. Overcamp for providing data from the meteorological tower at the Chalk Point power plant and to the Potomac Electric Power Company for furnishing power plant operating conditions. Finally, the assistance of C. Y. Li and W. Furth in analyzing the data is gratefully acknowledged.

TABLE OF CONTENTS

APPENDICES

FIGURES

TABLES

NOMENCLATURE

a_1	Dispersion coefficient; Equation 2 (m^{1-b_1})
a_2	Dispersion coefficient; Equation 2 (m^{1-b_2})
b_1, b_2	Exponents of distance in dispersion formulas; Equation 2
$c(x, y)$	Ground-level SO_2 concentration (ppb)*
c_m	Maximum predicted ground-level SO_2 concentration (ppb)*
c_p	Specific heat of air at constant pressure $(kcal/kg/^{o}K)$
$\bar{c}_s$	Time-averaged ground-level SO_2 concentration from stationary monitor; Figure 2 (ppb)
$c^i(t)$	Input SO_2 concentration to monitor at time t in time response tests; Equation B2 (ppb)
$c^o(t)$	Output SO_2 concentration from monitor at time t in time response tests; Equation B2 (ppb)
$\langle c \rangle_1$	Mean of maximum SO_2 concentration from repeated crosswind profiles on one measurement route; Figure 2 (ppb)
$\langle c \rangle_2$	Maximum SO_2 concentration from average crosswind profile; Figure 2 (ppb)
$\langle c \rangle_3$	SO_2 concentration from average crosswind profile at site of stationary monitor; Figure 2 (ppb)
cb	Background SO_2 concentration (ppb)
F	Buoyancy flux; $F = u_i g r_i^2 \; (T_i - T_a)/T_i$ (m^4/sec^3)
g	Gravitational acceleration (m/sec^2)
h_e	Effective stack height (m)

---

* ppb = parts per billion by volume. Dimensions of concentration consistent with variables in equations (1) and (3) are kg/m^3, $c(ppb) = c\ (kg/m^3) \cdot 0.13\ T_a \cdot 10^7$

h_s	Physical stack height (m)
H_m	Height of mixing layer (m)
k	Dimensionless coefficient in equation for x*; Equation D4
Q	SO_2 emission rate from stack (kg/sec)
Q_R	Solar heating rate (kcal/m^2/sec)
r_i	Stack exit radius (m)
s	Distance along measurement route (m)
sd_1, sd_2, sd_3, sd_s	Standard deviations in concentration about the averages $<c>_1$, $<c>_2$, $<c>_3$, $\overline{c}_s$, respectively (ppb)
t	Time (seconds)
T_a	Ambient air temperature (^oK)
T_i	Stack exit temperature (^oK)
u_i	Stack exit velocity (m/sec)
v	Wind speed (m/sec)
x	Distance from stack (m)
x_m	Distance from stack to predicted maximum concentration; Equation 4 (m)
x_2, x_3	Distance from stack to measured concentrations $<c>_2$ and $<c>_3$, respectively (m)
x*	Distance from stack where entrainment rate changes; Equation D4 (m)
y	Distance from plume axis in crosswind direction (m)
z	Height above ground (m)

α	Dimensionless coefficient in equation for c_m; Equation 3
β	Weighted time constant; Equation B2 (sec)
γ_1	Dimensionless coefficient; Equation B2
γ_2	Coefficient; Equation B2 (sec)
γ_3	Coefficient; Equation B2 (sec^{-1})
Δh	Plume rise; Equations D2 and D3 (m)
ϵ	Turbulent energy dissipation rate (m^2/sec^3)
η	Dimensionless proportionality constant relating surface heat flux ($=\eta Q_R$) to solar heating rate
θ	Potential temperature of atmosphere at height z (^oK)
$(\frac{\partial\theta}{\partial z})_n$	Initial potential temperature gradient of atmosphere ($^oK/m$)
λ	Dimensionless time response function; Equation B1
μ_1, μ_2	Dimensionless coefficients in time response function; Equation B1
ρ_a	Ambient air density (kg/m^3)
σ_y	Crosswind plume standard deviation (m)
$<\sigma_y>_1$	Average of measured crosswind standard deviations from a series of repeated concentration profiles; Figure 2 (m)
$<\sigma_y>_2$	Crosswind standard deviation from average crosswind concentration profile; Figure 2 (m)
σ_z	Vertical plume standard deviation (m)
σ_θ	Standard deviation of horizontal wind direction (degrees)
τ_1, τ_2	Time constants in time response function; Equation B2 (sec)
ϕ	Angular bearing of plume axis; Figure 1 (degrees clockwise from True North)
ϕ_2, ϕ_3	Angular bearing of concentration measurements $<c>_2$ and $<c>_3$, respectively (degrees clockwise from True North)

I. INTRODUCTION

Air quality impact assessments of fossil-fueled power plants rely strongly on mathematical simulations of the transport and dispersion of stack-emitted gases. From a description of the meteorology, surrounding terrain, and plant emission characteristics, mathematical models predict patterns of ground-level pollutant concentrations. The suitability of a power plant site or stack design is then determined by comparing calculated concentrations to ambient air quality standards.

In making an air quality assessment, we are faced with three difficult questions.

- What model should be used?
- How accurate is the model at any one site?
- How transferable is the model to another site and set of conditions?

This report addresses these questions by comparing predicted and measured ground-level sulfur dioxide concentrations downwind of three Maryland power plants.

The measurement data used in this report were obtained by Environmental Measurements, Incorporated (EMI), for the Maryland Power Plant Siting Program. Field programs were carried out at the Dickerson (Montgomery County), Chalk Point (Prince Georges County), and Morgantown (Charles County) power plants between October 1972 and June 1975. All three power plants are owned by the Potomac Electric Power Company. Previous reports (Weil 1973, 1974a, 1974b) described the measurement program and presented some comparisons between calculated and measured SO_2 concentrations at the Dickerson and Chalk

Point plants. This report summarizes the comparisons for all three power plants.

Measurement procedures were designed to gather air quality and meteorological data required for plume model evaluation. A mobile van was the primary means of acquiring the data. Sulfur dioxide was the principal pollutant measured because: (a) ambient air quality standards existed for SO_2; (b) rugged and reliable instrumentation was available for measuring SO_2; (c) emission rates were readily obtained; and (d) SO_2 was believed to be reasonably well conserved for travel times and distances of at least 1 hour and 20 kilometers, respectively. (This last reason was important for simplifying the modeling.) The program was aimed at measuring high SO_2 concentrations, which, for tall stack releases, generally occur during daytime and within a 10-kilometer distance of the stack. Field measurements are described in more detail in Section II.

The Gaussian plume model was chosen for evaluation because it is comparatively simple, realistic, and in widespread use. It accounts for the reduction in ground-level concentrations due to buoyant plume rise by assuming that the stack gases originate from an effective source height equal to stack height plus ultimate plume rise. (The plume rise models used in this analysis were those developed and satisfactorily tested in other studies.) Vertical and crosswind spread of the plume is specified as a function of distance and meteorology. Several empirical methods, based on different source and meteorological conditions, have been developed to predict plume dispersion in the Gaussian model. These include the approaches of Singer and Smith (1966) at the Brookhaven

National Laboratory, the Tennessee Valley Authority (TVA) (Thomas et al. 1970), Turner (1964), and Slade (1968). The major purpose of this report is to evaluate the relative merits of these approaches by comparing calculated and field-measured SO_2 concentrations.

To assess the site-specificity, if any, of modeling results, the comparisons were made at three power plants -- Dickerson, Chalk Point, and Morgantown -- that offered sufficient differences in terrain, stack height, and emission characteristics (Section II) to permit a reasonable test of model transferability. In addition, the power plants were sufficiently remote from other large sources of SO_2 that the SO_2 attributed to the plant could be ascertained easily.

The SO_2 concentrations were measured under all stability conditions. However, the analyses in this report are restricted to plume measurements made under unstable to slightly stable conditions because tall stacks in flat terrain usually do not produce high ground-level concentrations under stable conditions. Trapping of plumes within ground-based convective mixing layers capped by stable air is treated in the analysis. The Gaussian plume model is described in Section III, and its evaluation is presented in Section IV.

II. FIELD MEASUREMENTS

The coal-fired Dickerson power plant consists of three 185-MWe generating units with two 122-m stacks, 60 m apart. It is situated in the rolling terrain of Montgomery County, some 8 km east of the Catcoctin Mountains.

The coal-fired Chalk Point generating station faces the Patuxent River in southeastern Prince Georges County. The surrounding terrain is comparatively level. At the time measurements were made at Chalk Point (1973-1974), the plant had two 355-MWe generating units, with a 122-m stack on each, 40 m apart. (In 1975, a 600-MWe oil-fired unit, a 213-m stack, and a 122-m natural draft cooling tower were added.)

The Morgantown power plant is also situated in relatively flat terrain next to the Potomac River in southern Charles County. It has two 575-MWe generating units operating on either coal or oil or a mixture of the two. At Morgantown, boiler flue gases are exhausted through two 213-m stacks, 76 m apart.

At Chalk Point and Morgantown, air passage over large stretches of water during daytime may produce low altitude atmospheric cooling, resulting in an increase in atmospheric stability and a reduction in plume dispersion during over-water transport. The consequences of this phenomenon, as well as a few observations suggesting its occurrence at Morgantown and Chalk Point, are described in Section IV, C.

Measurements extended from October 1972 through April 1973 at Dickerson, from September 1973 through June 1974 at Chalk Point, and from February 1975 through June 1975 at Morgantown. Stack emission conditions were computed from hourly operating logs on fuel consumption, generating load, and the gas temperature, and from weekly analysis of fuel sulfur content. Ranges of stack SO_2 emission rates and buoyancy fluxes for the three plants are presented in Table 1. (Some of the measurements at Chalk Point and Morgantown were obtained with only one unit in operation.)

An instrumented mobile van was used to measure ground-level SO_2 concentrations and overhead SO_2 and NO_2 burden. Overhead burden is the vertically integrated gas concentration (SO_2 or NO_2) along a line extending from the measuring instrument (a Barringer Correlation Spectrometer) through the elevated plume. The primary purpose in measuring burden was to locate and track the plume remotely, especially when the SO_2 or NO_2 had not yet reached the ground. Once the plume was located, the SO_2 ground-level concentration, the key parameter of interest, was then measured with a flame photometric gas analyzer (manufactured by Meloy Laboratories).

Repeated passes transverse to the direction of plume travel were made along available roads. The measurements proceeded from ambient SO_2 levels on one side of the plume, through the plume, and out to ambient SO_2 concentrations on the opposite side of the plume. The time required for a series of replicate passes (usually six per series), was typically 1/2 to 1-1/2 hours. Figure 1 shows the instantaneous and time-averaged plume, the mobile van, and the measurement routes. Details of experimental procedures are described in Jepsen and Weil (1973).

Table 1. Power Plant Emission Characteristics, Meteorological Conditions, and Plume Measurements.

	Dickerson	Chalk Point	Morgantown
Stack Height[1] (m)	122	122	213
Distance Between Stacks (m)	60	40	76
Stack Diameter at Top (m)	5	5	6
SO_2 Emission Rate (kg/sec)			
Stack 1	0.33 - 1.02	0.45 - 1.48	1.37 - 2.03
Stack 2	0.35 - 0.55	0.73 - 1.29	1.45 - 2.03
Buoyancy Flux[2] (m^4/sec^3)			
Stack 1	130 - 452	163 - 526	518 - 772
Stack 2	125 - 237	239 - 408	531 - 738
Mean Wind Speed (m/sec)	0.7 - 15.7	1 - 11.8	1.6 - 11.3
Mixing Depth (m)	300 - 2500	300 - 2300	520 - 2400
Maximum SO_2 Concentration (ppb)			
From average crosswind profile	9 - 165	4 - 278	7 - 322
Average of peaks from repeated profiles	11 - 302	7 - 477	9 - 414
Distance Downwind Covered by Measurements (km)	1.7 - 19	2.8 - 33	2.7 - 32
Total Number of Crosswind Profiles	225	336	127

1 Each power plant had two stacks.

2 Briggs (1970) definition of buoyancy flux

Measurements of SO_2 concentration by a stationary monitor were obtained concurrently with those by the mobile van. The stationary monitor was placed in a self-powered van, so that it could be located at several sites in the plume (see Fig. 1), and was positioned as close to the plume centerline as possible, as determined from mobile van traverses. It was usually left at one position for about one hour. A flame photometric gas analyzer (either a Meloy or Bendix instrument) was used for measuring SO_2.

Calibrations on the Meloy monitor used in the mobile van were performed daily, at the beginning and completion of the measurements. At Dickerson and Chalk Point, the monitor generally read to within 15 per cent of the calibration gas concentration, a sufficiently small difference to justify our using the Dickerson and Chalk Point SO_2 measurements without correcting for instrument calibration. During the Morgantown measurement program, however, the Meloy monitor read between 60 and 115 per cent of calibration gas concentrations, and adjustments were made to the Morgantown measurements to correct for the differences. With some exceptions, the stationary monitor was calibrated daily, and correction factors were applied where necessary.

The centroid, crosswind standard deviation (σ_y), and peak concentration for each individual SO_2 ground-level concentration profile were calculated.* Crosswind standard deviation was computed by taking second moments of the concentration distribution about the centroid, taking into account the angle of the road with respect to the wind direction.

*Background SO_2 concentrations (typically 10 ppb to 15 ppb) were subtracted from the SO_2 concentration measurements to obtain SO_2 due to the power plant alone. The typical error in background concentration, resulting from variations in background levels and instrument accuracy, is estimated to be 5 ppb.

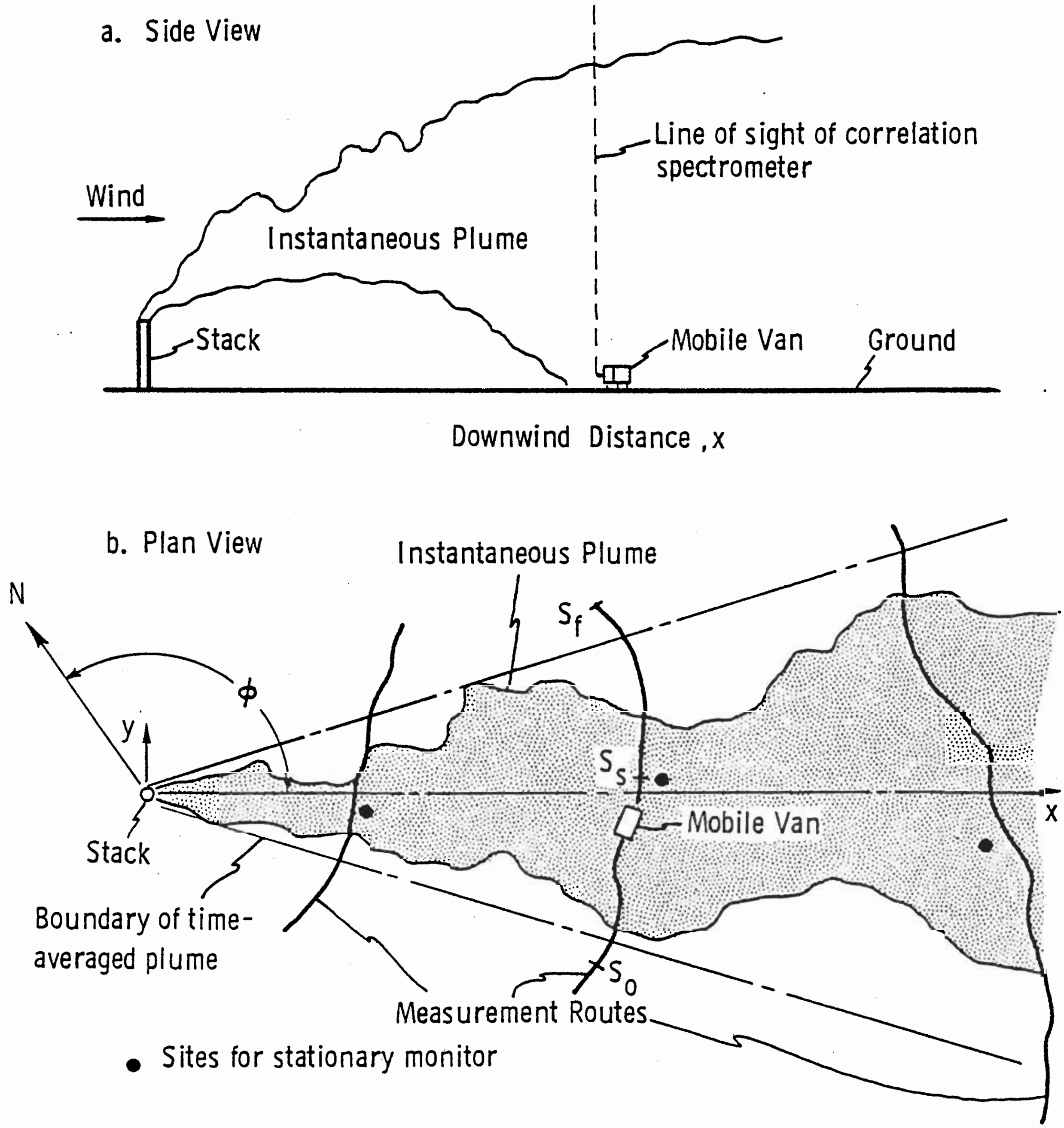
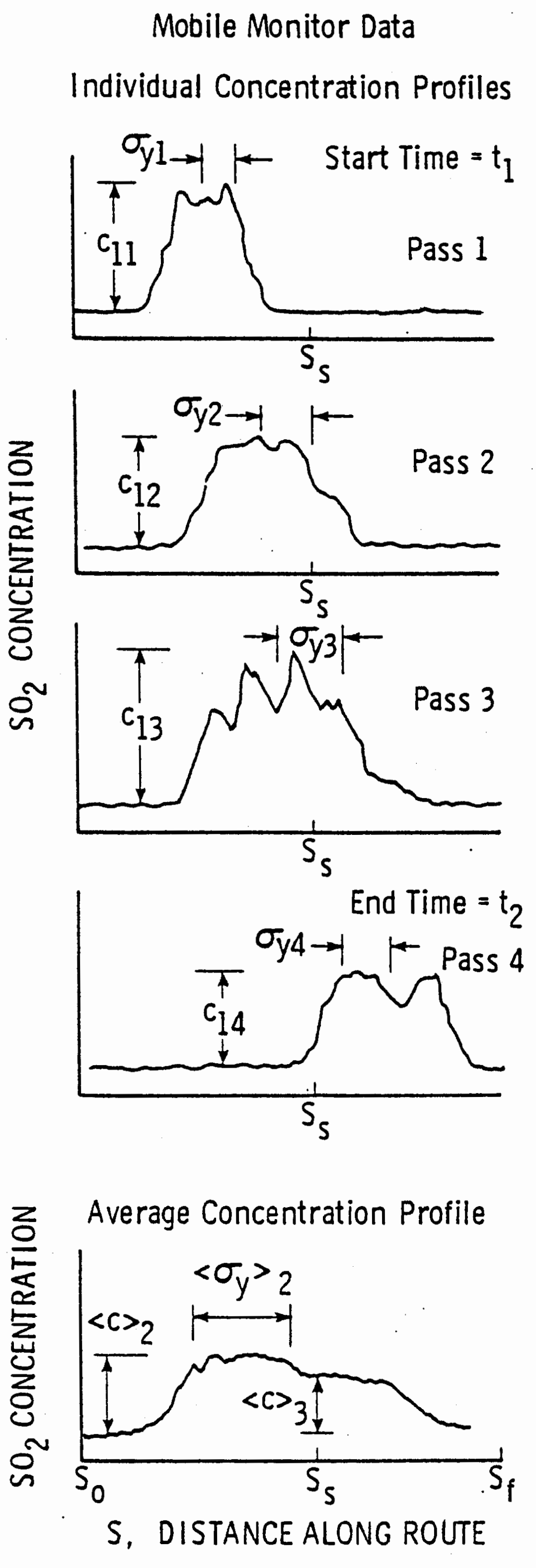


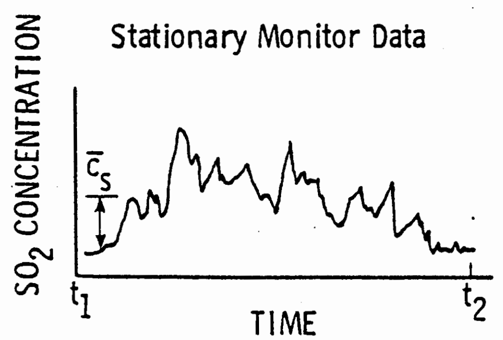
Fig. 1. Schematic of plume showing position of monitoring vehicles.

Mean values of crosswind standard deviation, $<\sigma_y>_1$, and peak concentration, $<c>_1$, from a series of repeated passes were used as approximations of plume properties for an averaging time of about 10 minutes.

Also, an average concentration profile for each series of repeated passes was determined from the average concentration at 100 equally spaced angular intervals across the composite plume path. For this average profile, the centroid, crosswind standard deviation, $<\sigma_y>_2$, and maximum concentration, $<c>_2$, were found. The average profile is an approximation of the time-averaged profile which would be obtained by a network of fixed monitors along the measurement route. Figure 2 illustrates individual and average SO_2 profiles obtained along a measurement route in Figure 1. The maximum concentration and crosswind standard deviation are denoted for each profile.

As a consistency check, time-averaged SO_2 concentrations, computed from the continuous SO_2 measurements by the stationary monitors, were compared to SO_2 concentrations from the "average profile" determined by mobile van measurements made along the same route (see Appendix A). (Similar comparisons have also been made by Jepsen and White, 1975.) At Morgantown, the ratio of mobile van concentration to time-averaged concentration, based on 10 comparisons, had an arithmetic mean of 0.85 with an estimated error in the mean of 0.25. At Chalk Point, the mean ratio, based on 4 comparisons, was 0.76 with an estimated error of 0.16. The estimated error at Chalk Point





Individual Concentration Profiles

$<c>_1 = \frac{1}{4}\sum_{i=1}^{4} c_{1i}$, average peak concentration

$<\sigma_y>_1 = \frac{1}{4}\sum_{i=1}^{4} \sigma_{yi}$, average crosswind standard deviation

Average Concentration Profile

$<c>_2$ = maximum concentration

$<c>_3$ = concentration at location of stationary monitor

$<\sigma_y>_2$ = crosswind standard deviation

Stationary Monitor

$\bar{c}_s$ = time averaged concentration between t_1 and t_2

Figure 2. Schematic of individual and average crosswind concentration profiles obtained in mobile van and time dependent concentration obtained in stationary van. Positions along measurement route of mobile van depicted in Fig. 1.

is less than that required to account for the deviation of the mean from the ideal ratio of 1.0.

Differences between SO_2 concentrations from the average profile and time-averaged concentrations were believed due, in large measure, to the time response of the Meloy monitor. A study of the Meloy (model SH 202) time response was made to ascertain its effect on measured crosswind SO_2 profiles. Test results indicated that monitor time response could explain the lower concentrations obtained with the mobile van. Details of the study are discussed in Appendix B.*

Meteorological variables were obtained throughout the day at each plant. Vertical profiles of wind speed and direction were measured hourly either by theodolite-tracked pilot balloons or by radiosonde tracking. Vertical profiles of temperature were measured two or three times a day either from radiosondes or with an instrumented airplane. In addition, radiosonde temperature profiles were obtained from the Patuxent Naval Test Center and Dulles Internationl Airport.

The height of convective mixing layers was determined from observed temperature profiles. It was defined as the altitude where the temperature gradient first became isothermal above a ground-based, nearly adiabatic air layer, and remained so for at least 50 m. (Within convective mixing layers, the vertical temperature gradient is quite close to dry adiabatic while, above the mixing region, the air is quite stable.) Mixing depths were interpolated at times between measured temperature profiles with the aid of a simple model (Appendix C).

---

*Individual and average crosswind SO_2 profiles used in the model evaluation were not corrected for instrument time response because response functions for all monitors used in the study were not available.

The vertical temperature gradient used to compute plume rise was the best fit, either by a least squares fit or by eye, to the temperature profile between stack top and the top of the mixing layer. Wind speed used in model calculations was an average value over the same altitude range.

Wind and temperature difference measurements also were recorded on a 100-m tower at Chalk Point (wind at 10 m, 50 m, and 100 m; air temperature difference between 10 m and 100 m). The standard deviation, σ_θ, in horizontal wind direction, computed from the tower measurements, was employed in selecting dispersion coefficients at Chalk Point (Section IV). Surface weather observations were obtained from Washington National and Dulles International Airports and were used to select Pasquill dispersion coefficients by the Turner (1964) approach (Section IV).

The range of meteorological variables and plume SO_2 concentrations for the three power plants are given in Table 1. A list of plume measurements, meteorological variables, and plant emission conditions for each of the 126 cases analyzed is given in Appendix E.

III. GAUSSIAN PLUME MODEL

The time-averaged dispersion of buoyant plumes from tall stacks is simulated in a realistic and straightforward manner by the Gaussian plume model (Pasquill, 1974). In this model, the ground-level concentration, c, of stack-emitted sulfur dioxide varies as

$$c(x, y) = \frac{Q}{\pi v \sigma_y \sigma_z} \exp \left\{ - \frac{h_e^2}{2\sigma_z^2} - \frac{y^2}{2\sigma_y^2} \right\} \qquad (1)$$

where

Q = SO_2 emission rate (kg/sec)

v = wind speed (m/sec), assumed to be uniform with altitude

σ_y, σ_z = crosswind and vertical plume standard deviations (m), functions of x

h_e = effective stack height (m), equal to physical stack height plus plume rise

x = downwind distance from the power plant (m)

y = crosswind distance from the plume axis (m)

In this analysis, the effective stack height is assumed to be constant (not a function of downwind distance as in some models e.g., Csanady, 1973). Plume rise is calculated from the formulas of Fay et al. (1970) and Briggs (1970). These formulae and their applicability are discussed in Appendix D.

For the distance range of interest in the analysis (1 km to30 km), we approximate the plume standard deviations by power law functions of distance x given by

$$\sigma_y = a_1 x^{b_1}$$
$$\sigma_z = a_2 x^{b_2} \quad . \tag{2}$$

The coefficients a_1, a_2 and exponents b_1, b_2 depend on meteorological conditions or the "stability class." A critical problem is choosing the technique for prescribing a's and b's that gives the most realistic predictions of dispersion and ground-level concentrations. (Values of a_1, a_2, b_1, and b_2 for different methods of determining stability are given in Appendix D.)

With the above expressions for σ_y and σ_z, the maximum ground-level concentration is

$$c_m = \frac{Q\alpha^{\alpha/2}}{\pi v a_1 a_2} \quad \frac{\exp(-\alpha/2)}{(h_e/a_2)^{\alpha}} \tag{3}$$

where $\alpha = 1 + b_1/b_2$. The downwind distance x_m to the maximum concentration is

$$x_m = \left(\frac{h_e}{\sqrt{\alpha} \quad a_2} \right)^{1/b_2} \quad . \tag{4}$$

These expressions for c_m and x_m apply to a plume which is perfectly reflected at ground but is unrestricted in spreading above the plume centerline. However, the vertical spread of a plume is often limited by the presence of an elevated stable air layer above a ground-based mixing layer. For the case where there is perfect reflection of the plume by a stable layer above the effective stack height, we have used Scriven's (1967) modification to the standard Gaussian plume equation. We then obtain an equation for the normalized ground-level concentration c/c_m, along the plume axis ($y = 0$):

$$\frac{c}{c_m} = \frac{\exp(\alpha/2)}{(x/x_m)^{\alpha b_2}} \sum_{n=-\infty}^{\infty} \exp\left(-\frac{\alpha}{2}\left(1 - 2n\frac{H_m}{h_e}\right)^2 (x/x_m)^{-2b_2}\right) \qquad (5)$$

where H_m is the height of the stable air layer above ground (H_m must be equal to or greater than h_e). The expressions for c_m and x_m and equation (5) have been given in other reports by Weil (1974a, 1974b). Other details of the modeling are contained in Appendix D.

Methods used in predicting dispersion, and hence c_m, x_m, α, and b_2 are evaluated in Section IV.